# Measuring Cosmological Parameters

Baryon Density Parameter

- Up to now we met three cosmological parameters: $H_0, \Omega_M, \Omega_\Lambda$. There is another important parameter: the density of baryons.

- Now we know that in addition to ordinary (***baryonic***) matter, universe contains the so called "dark matter"'. Thus, we need to know the relative contributions of those two kinds of matter.

Baryon Density Parameter

- The density of baryons can be also expressed as an "Omega" parameter Ω_B. Of course, $\Omega_B \leq \Omega_M$ and $\Omega_B = \Omega_M$ only if there is no dark matter whatsoever.
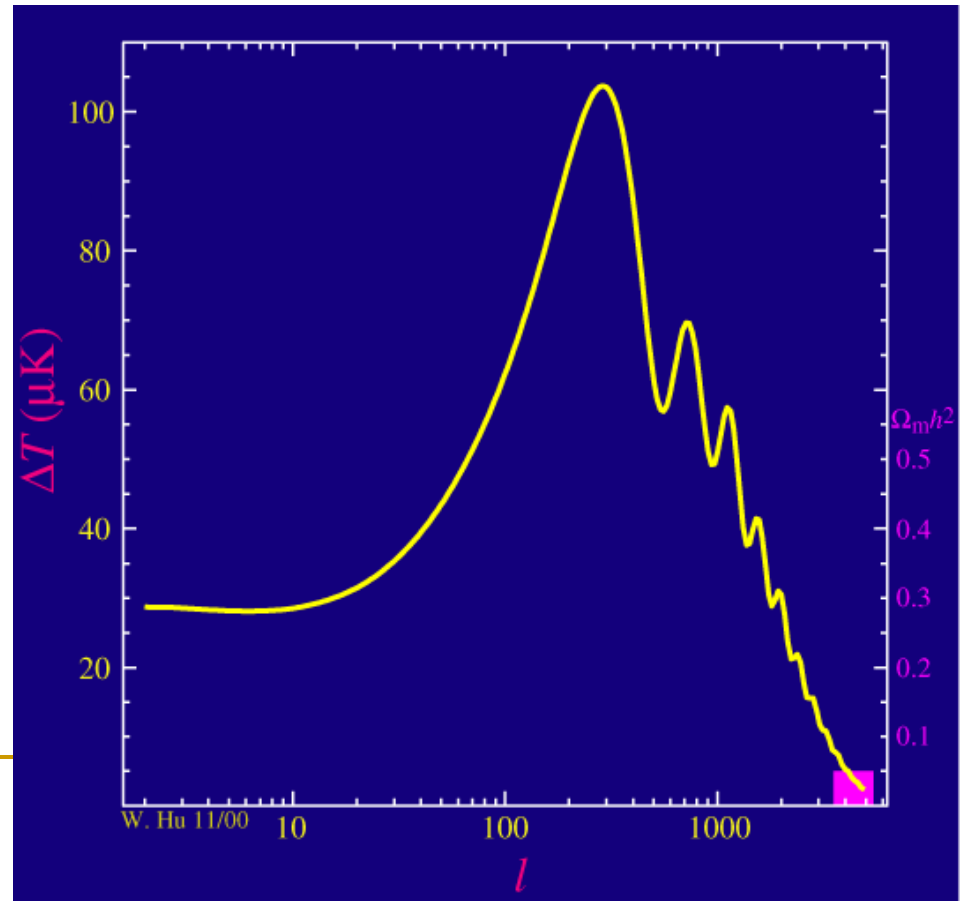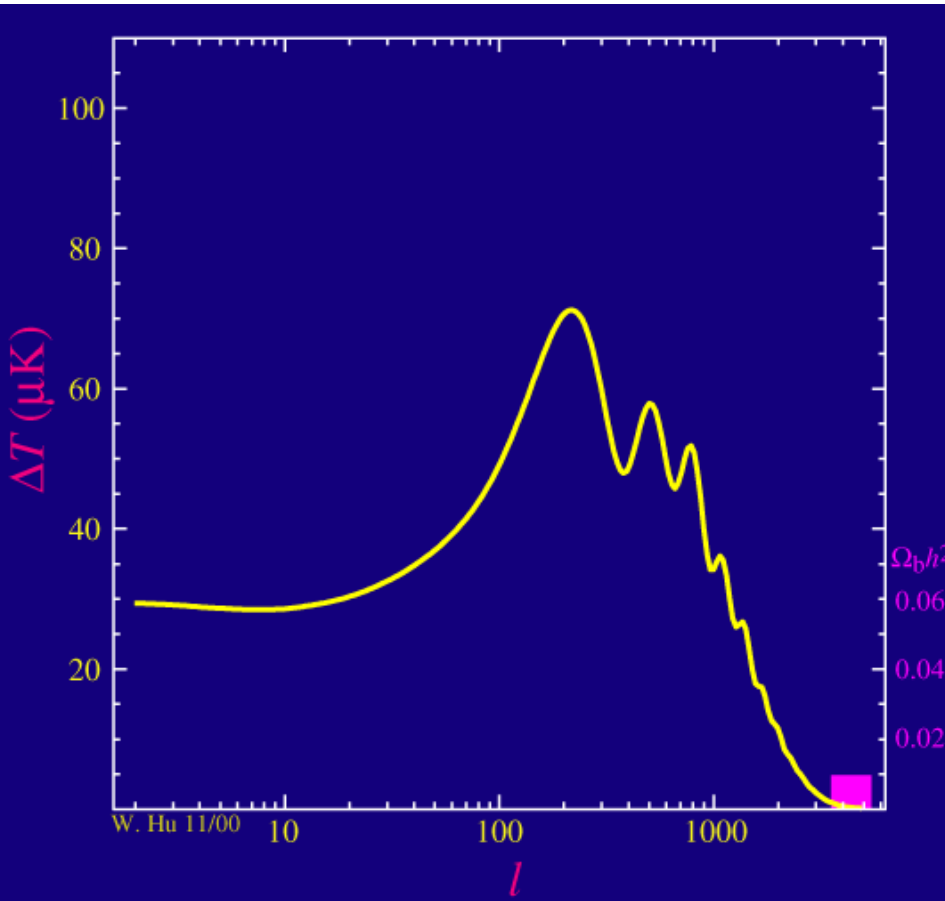
Measuring Cosmological Parameters

- Recall: the CMB spectrum is a "fingerprint" of the whole universe. We can read all parameters off that chart.
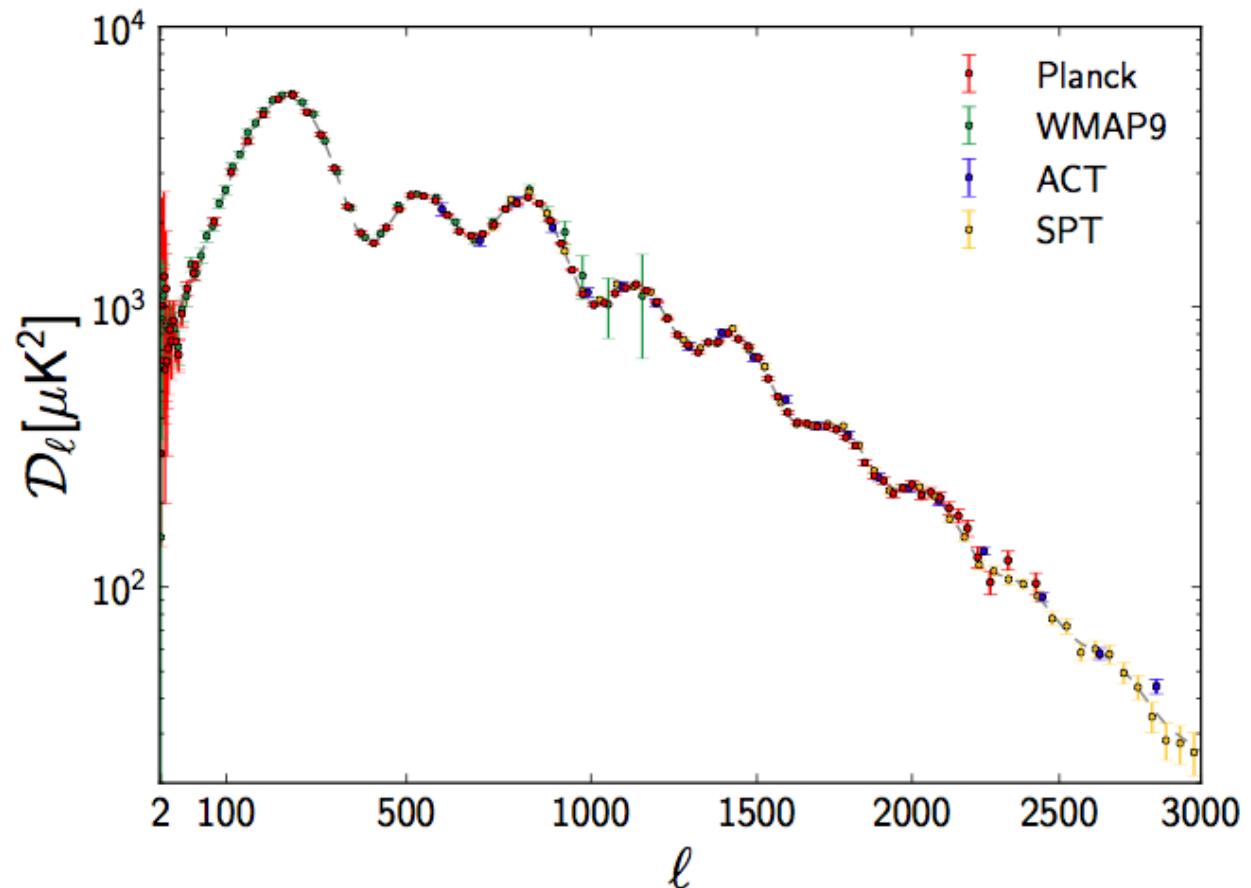
The Power of CMB

- The right shape of the spectrum only comes with the right values of the parameters.

Geometry

- CMB does everything well, but one thing it does best – tells us the geometry of the universe.

- Ever since the first balloon-based experiments in 1998 we knew the universe is consistent with being flat.

- Now Planck tells us: space within our cosmic horizon is curved by not more than 1%.

- We live in flat space!!! Through away your non-Euclidean geometry textbook.

Measuring Cosmological Parameters

- Recall: any scientific measurement is required to be objective, i.e. independently verified.

- Hence, it is not just enough to take the parameter values from, say, Planck and relax. All such measurements need to be verified with other methods.

Baryon Density

- One of the best ways to measure Ω_B is to study the Big Bang Nucleosynthesis (recall the origin of chemical elements).

- During this process, in addition to helium (^{4}He), a few other elements are produced: deuterium, helum-3, and lithium-7 (denoted as D, ^{3}He, and ^{7}Li).

- The amount of those isotopes produced depends on the density of baryons, i.e. on Ω_B.

Baryon Density

- The abundances of these elements can be measured quite accurately, and the latest result is
  - BBN: $\Omega_B = 0.0467 \pm 0.0026$
  - WMAP: $\Omega_B = 0.0463 \pm 0.0024$
  - Planck: $\Omega_B = 0.0486 \pm 0.0007$

- Two different methods, three different, completely independent observations.

Never Ending Story: Hubble Constant

- Hubble himself obtained the value for H_0 of 500 km/s/Mpc. That was way too large, and such a universe would be younger than the Earth.

- In 1952 Walter Baade showed that there were two types of Cepheid variables, and that Hubble mistook one type for another. That reduced the Hubble constant to 200, still too large.

- In 1958 Alan Sandage found another error in original Hubble's analysis, and found H_0 between 50 and 100 km/s/Mpc.

Hubble Constant

- Until 1996 the Hubble constant floated between 50 and 100, depending on who measured it and what method was used.

- In 1996 *Hubble* found Cepheid variables in a distant galaxy M100, and using them a much more accurate value of $H_0 = 70 \pm 8\,\mathrm{km/s/Mpc}$ was measured.

- After that the ball got rolling really fast...

Hubble Constant

- By now there are several different methods that give rather accurate measurements, and CMB is, of course, among them.

  - Planck: $H_0 = 67 \pm 1.2\,\mathrm{km/s/Mpc}$
  - WMAP: $H_0 = 70 \pm 2.2\,\mathrm{km/s/Mpc}$
  - Water maser: $H_0 = 69 \pm 7\,\mathrm{km/s/Mpc}$
  - Cepheids: $H_0 = 74 \pm 2.4\,\mathrm{km/s/Mpc}$

- Craig's interactive plot.

The age of the universe

- We cannot directly measure the age of the universe, but we can measure the ages of various astronomical objects. Hopefully, a mother is older than a daughter.

- The age of the Earth and the solar system can be measured by means of *radioactive dating*: 4.6 billion years.

- The age of white dwarfs can be measured rather accurately by studying their cooling. The oldest white dwarfs are 10 billion years.

The age of the universe

- The age of stars can also be determined using theoretical models. The oldest stars are found to be about 13 billion years. This "measurement" however is partly based on theoretical modeling, and thus may contain a systematic error.

- Finally, CMB is always the last resort:
  - WMAP: $\qquad t_0 = 13.74 \pm 0.11\,\mathrm{Gyr}$
  - Planck: $\qquad t_0 = 13.796 \pm 0.058\,\mathrm{Gyr}$

Matter Density

- To measure Ω_M, we need to measure the amount of matter in the universe, i.e. "weight" the whole universe. We can measure all the matter in galaxies using the Kepler's third law: we know how large the galaxies are, and how fast they rotate. But how do we account for the stuff that is *not* in the galaxies?

- Basically, we need something that is *fair sample* of the universe as a whole.

Matter Density In Clusters

- Astronomers often make *an assumption* that clusters of galaxies are fair samples of the universe, i.e. they on average contain the same ratio of the dark matter to the visible matter (gas and stars) as the universe in the whole.

- The primary reason is that the largest clusters are so big, there is no known way to escape their gravity.

$$\frac{\Omega_B}{\Omega_M} = \frac{M_{\mathrm{vis}}}{M_{\mathrm{tot}}}$$

Dark Matter

- **The Results:**
  - ❑ Clusters: $\Omega_M = 0.255 \pm 0.056$
  - ❑ WMAP: $\Omega_M = 0.279 \pm 0.025$
  - ❑ Planck: $\Omega_M = 0.314 \pm 0.020$
- **What is very surprising about this result?**
  - A. Ω_M is less than 1.
  - B. Different values do not agree
  - C. The measurement error is too large.
  - D. Cluster value is substantially below the CMB measurements.

Dark Energy

- If the universe flat, then $\Omega_{\mathrm{TOT}} = 1$.

- If $\Omega_M \approx 0.3$, then the only choice is that $\Omega_\Lambda \approx 0.7$

- Dark Energy actually exists!

Dark Energy

- The Dark Energy story actually begins earlier.

- In 1998 two independent groups used thermonuclear supernovae (SNIa) to measure the rate of expansion of the universe.

- They both discovered that the expansion of the universe actually *accelerates*.

- Recall that normal gravity slows down the expansion.

Dark Energy

- The conclusion from that observation is that
  - either there must exist a new substance (we call it Dark Energy) whose gravity is repulsive
  - or
    - A. General Relativity is wrong.
    - B. Supernovae do not exist.
    - C. Their telescope was broken.
    - D. They did not account for light aberration.

Dark Energy

- While it is possible that Einstein got it wrong, the existence of Dark Energy is generally considered to be a more likely explanation.

- Funny fact: we actually know how much of it there is: $\Omega_\Lambda = 0.686 \pm 0.020$, but we don't know what it is.

- All we can measure is how Dark Energy evolves in time. This evolution is quantified by the "equation of state parameter" w. If $w = -1$, then Dark Energy is just a plain cosmological constant.

Exploring The Dark Energy

- We measure the properties of Dark Energy very indirectly – only through its effects on the expansion rate of the universe.

- Dark Energy only dominated the expansion recently.
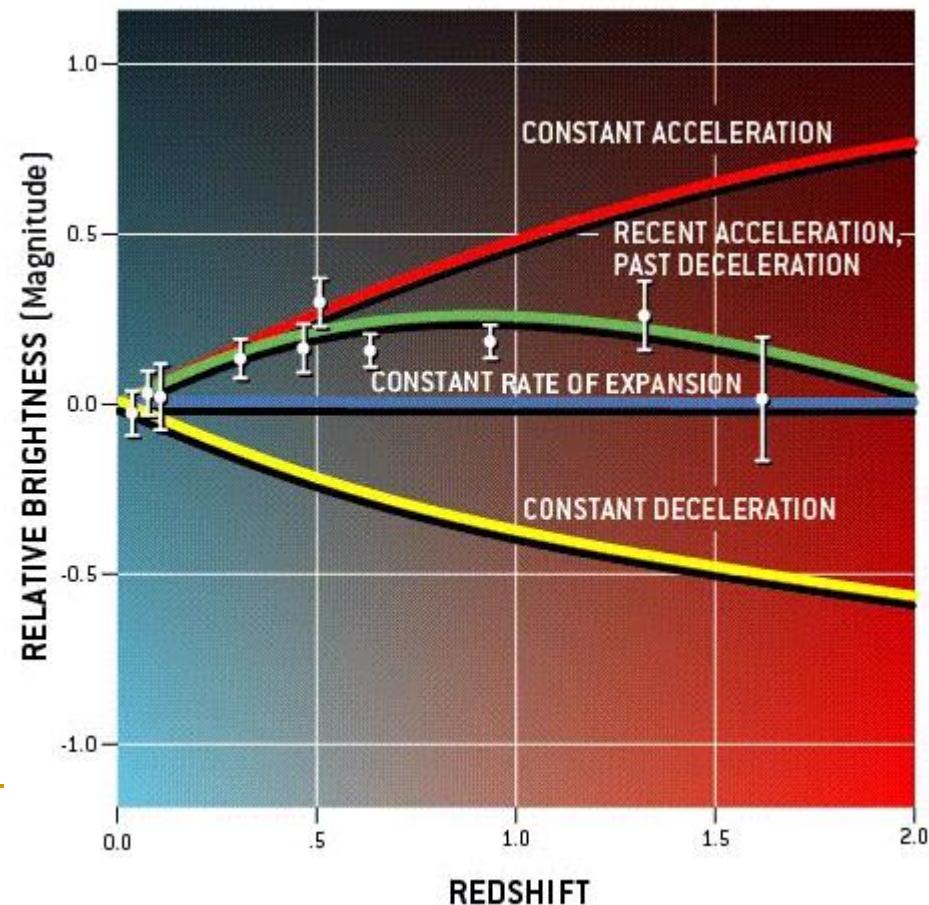
Exploring The Dark Energy

- Several methods exists for such a study:
  - Supernovae are the first and still highly used method.
  - Gravitational lensing depends on where objects in the universe are, hence on how it expanded in the past.
  - "Baryonic Acoustic Oscillations" (BAO) method uses the pattern of the CMB as a "standard ruler" to compare all sizes to.
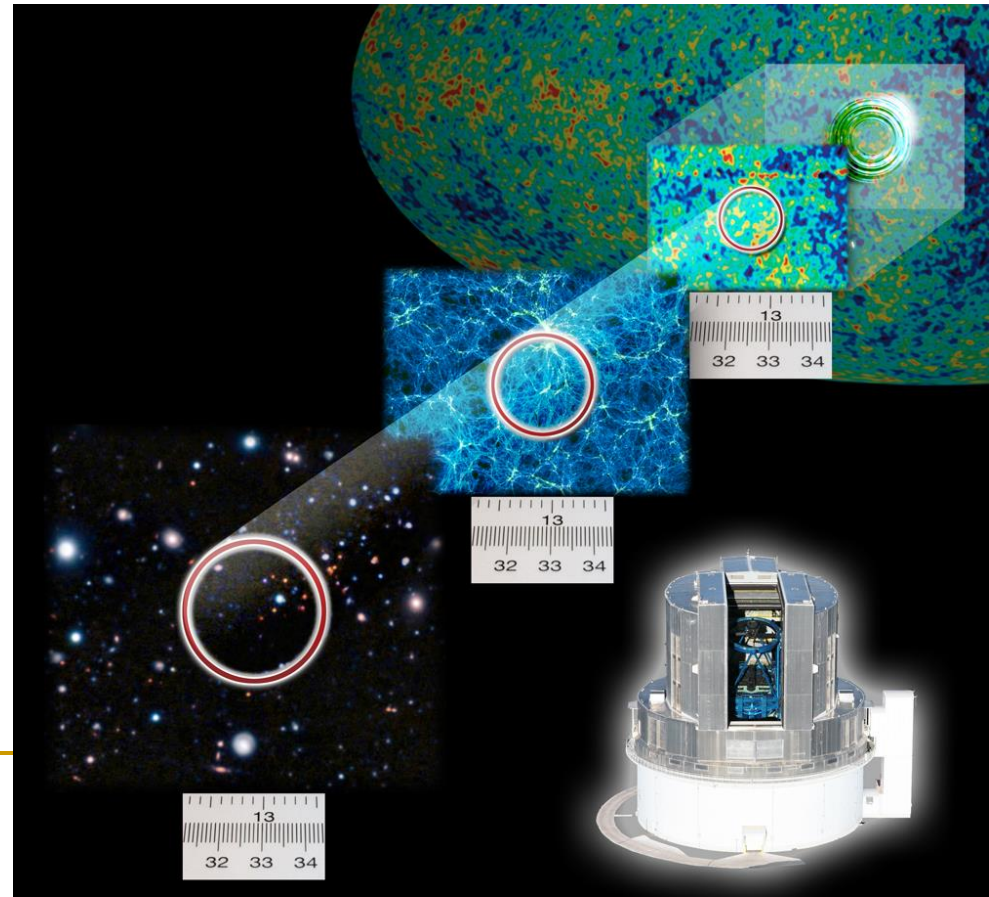 - CMB
  - and the list goes on...

Weak Lensing

- One of the most powerful methods to study Dark Energy.
- Shapes of distant galaxies are affected by the matter distribution between them and us.
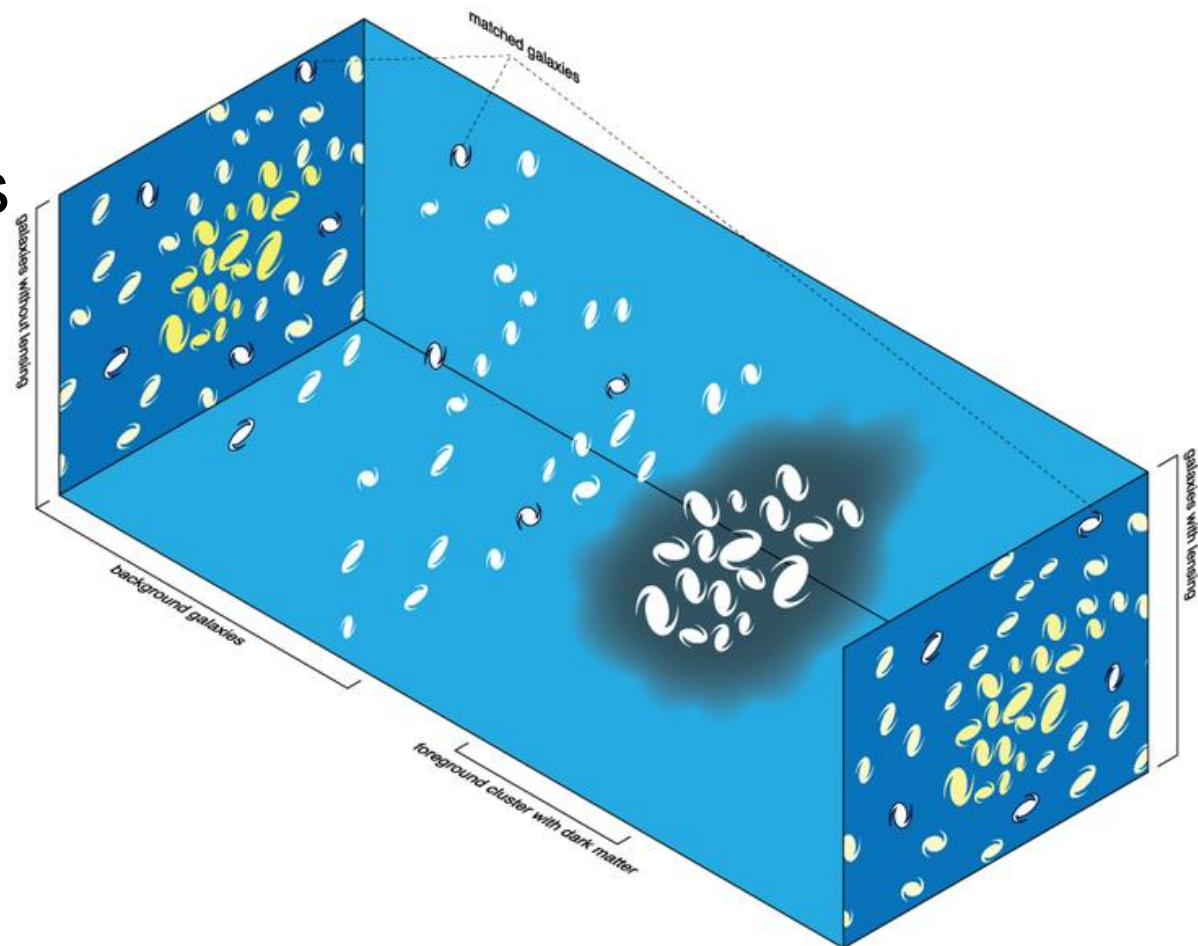
Baryonic Acoustic Oscillations (BAO)

- Bumps and wiggles in the CMB also leave (very small) imprints in the distribution of galaxies on the sky.

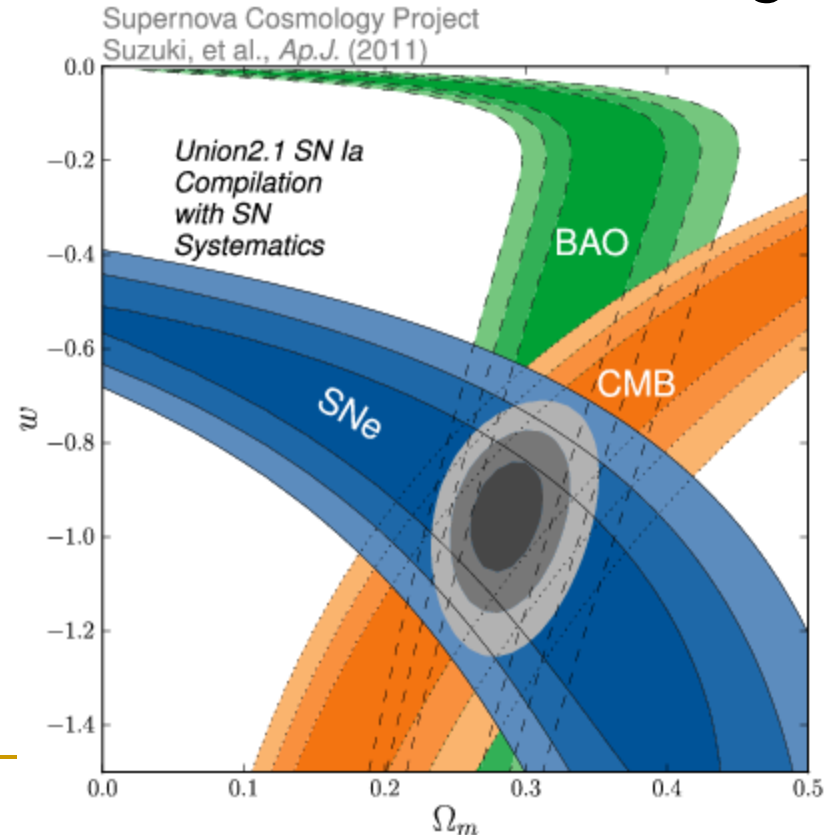- This pattern serves as a "standard ruler".

Parameter "Degeneracies"

- Why do we need all these methods? Because different parameters "talk to each other".

- For example, SNe measure the expansion rate. If there is less matter (Ω_M is small), then the dark energy does not need to be so repulsive (w can be larger than -1) to counteract the gravity of matter. Hence, the same expansion rate can be arranged for different pairs of values (Ω_M, w).

- This is called a "degeneracy" or "correlation" between the parameters.

Taking It All Together

- None of the methods is perfect.

- The real power of these methods is in *combining* them together.

- For example, CMB and SNe trade-off between Ω_M and w in the opposite ways.

Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)

Union2.1 SN Ia Compilation with SN Systematics

Future

- Exploring Dark Energy is the primary focus of modern cosmology. Several big observational surveys are in process right now, and even bigger ones are in the plans.

- Dark Energy Survey (DES) is an international project in which UChicago and Fermilab play the leading role.

- It will map 300 million galaxies.

Future

- The-biggest-ever project is Large Synoptic Survey Telescope (LSST).

- It will map ½ of the sky to ½ age of the universe (some 25 billion galaxies).

- It will collect more data then all previous observations taken together.
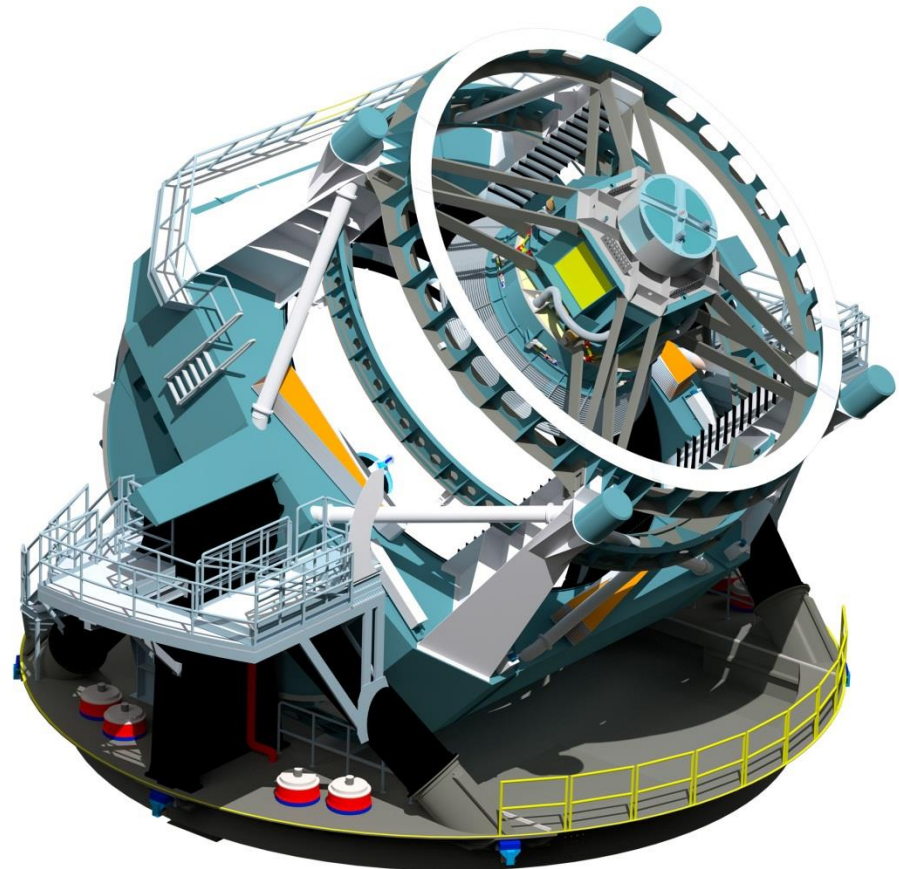
Believe it or not…

- We only ever detected 5% of the whole contents of the universe.

Composition of the universe

- Dark energy
- Dark Matter
- Baryons

70% 25% 5%